

## BINARY STUDIES WITH THE NAVY PRECISION OPTICAL INTERFEROMETER

C. A. HUMMEL<sup>1</sup>, R. T. ZAVALA<sup>2</sup> and J. SANBORN<sup>3</sup>

<sup>1</sup>*European Southern Observatory, Karl-Schwarzschild-Str. 2,  
85748 Garching, Germany*

<sup>2</sup>*U.S. Naval Observatory, Flagstaff Station, 10391 W. Naval Obs. Rd,  
Flagstaff, AZ 86001, USA*

<sup>3</sup>*Lowell Observatory and Northern Arizona University,  
Flagstaff, AZ 86001, USA*

**Abstract.** We present recent results from observations of binary and multiple systems made with the Navy Precision Optical Interferometer (NPOI) on  $\zeta$  and  $\sigma$  Orionis A,  $\xi$  Tauri, HR 6493, and b Persei. We explain how the orbital modeling is performed and show that even triple systems can be constrained with the data.

**Key words:** interferometry - binaries

### 1. Introduction

Observations of binary stars are the bread-and-butter for optical interferometers. An easy exploit for the unrivaled angular resolution of long baseline interferometers, the measurement of the orbits of double-lined spectroscopic binaries affords the determination of fundamental parameters of stars as well as their distance from Earth. Interferometry thus extends the reach of using spectroscopic binaries to non-eclipsing pairs, as a special but unlikely geometry for seeing eclipses, which also allow the determination of high-precision stellar masses, is no longer required.

After about a decade of developing the technique of long baseline optical interferometers, i.e. those combining independent telescopes observing in the visual or near-infrared bands with baselines in between them ranging from a few meters to over a hundred, three major facilities are now available for regular scientific observations, CHARA on Mt Wilson, California, NPOI on Anderson Mesa, Arizona, and VLTI on Cerro Paranal, Chile. All three of them have the capability of reconstructing images from the visibility data they record, due to the fact that they combine the light of three or more

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>2013</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2013 to 00-00-2013</b>	
4. TITLE AND SUBTITLE <b>Binary Studies With The Navy Precision Optical Interferometer</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>U.S. Naval Observatory,Flagstaff Station,10391 W. Naval Obs. Rd,Flagstaff,AZ,86001</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>Cent. Eur.Astrophys.Bull. 37 (2013) 1, 127?135</b>					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>10</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

telescopes at the same time.

Here we report on recent observational results from NPOI in the area of binary and multiple star research.

## 2. The NPOI

The NPOI was described by Armstrong *et al.* (1998). In operation since 1996 (Benson *et al.*, 1997), its design has been optimized for imaging applications and allows the simultaneous combination of up to six telescopes (Hummel *et al.*, 2003). The visible band is recorded in 16 channels between 550 nm and 850 nm, and therefore increases the aperture plane coverage for broadband applications (Hummel, 2010).

At the time of this writing, NPOI offers baselines between 17 m and 80 m, with a resolution of 1.5 mas in the bluest channel. Different baseline configurations can be realized by moving the siderostats (afocal telescopes) to different stations along the three arms of a “Y”. More than 200 observations of stars can be recorded in a single night if the conditions are very good.

Each observation provides the amplitude of the visibility function for a number of baselines and as a function of wavelength. Also, limited visibility phase data are obtained, which allow the unambiguous determination of the target orientation on sky. Together, these data will constrain separation and position angle of a binary, as well as the magnitude difference as a function of wavelength and, if the stellar disks are large enough, the apparent diameter of the binary components.

## 3. Recent Results

In Table I we list the preliminary orbital elements from interferometry for the individual systems discussed in the following sections.

### 3.1. $\zeta$ ORIONIS A

Component A of this multiple system was found to be double by Hummel *et al.* (2000), and NPOI observations of the 7 year orbit are now complete (see Figure 1). Preliminary results were reported by Rivinius *et al.* (2011), including a mass of  $24.8 \pm 5.6 M_{\odot}$  for the O9.7 supergiant primary. Meanwhile, another high-precision measurement was taken with the UVES

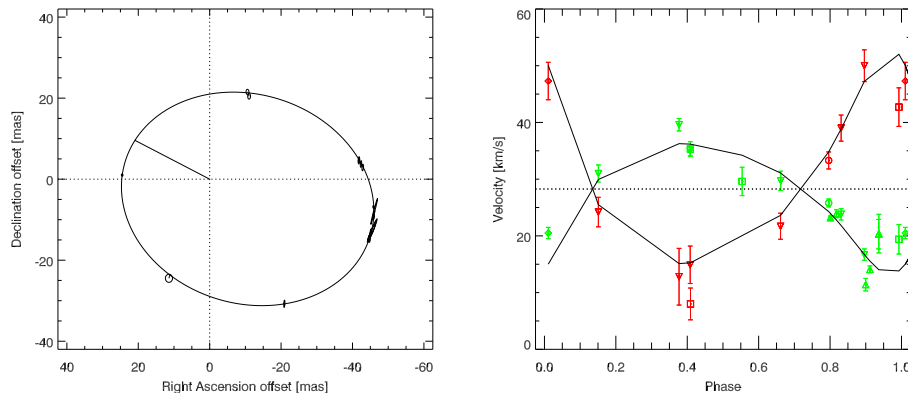


Figure 1: Orbits of  $\zeta$  Orionis A. Velocities of the primary are in green, velocities of the secondary in red. The spectrometers used for the measurements are labeled as follows: UVES (diamond), HEROS/FEROS (triangle down), ELODIE (squares), FOCES (circle), BES0 (triangles up).

**Table I:** Preliminary orbital elements

Parameter	$\zeta$ Ori A	$\sigma$ Ori A	$\xi$ Tau	HR 6493
Period [d]	2689	143.2	145.2	26.28
Semi-major axis [mas]	36.0	4.3	15.9	7.7
Inclination [deg]	139.7	56.3	87.1	57.1
Eccentricity	0.336	0.78	0.21	0.49
Periastron [deg]	204.1	202.2	157.9	198.4
Epoch MJD	52732	54162.7	53710.4	48102.4
Ascending node [deg]	84	7.5	148.4	305.6

spectrometer on VLT, the the mass estimates were revised to  $14.8 \pm 2.6 M_{\odot}$  and  $9.0 \pm 1.2 M_{\odot}$  for primary and secondary, respectively. The spectroscopic orbit is also shown in Figure 1, derived from additional archival data. The dynamical parallax corresponding to the orbits shown is  $3.3 \pm 0.2$  mas.

### 3.2. $\sigma$ ORIONIS A

Component A (O9.5V) of this multiple system (whose E component has achieved fame for its magnetic field) was identified as a binary by Bolton

(1974), and Simón-Díaz *et al.* (2011) were the first to obtain solutions for the radial velocity curves of both components.

This system was first resolved by NPOI in 2000, but subsequent observations proved to be very difficult as strong interference fringes could not be found easily. Due to the lack of a good model, predictions for the best baseline configuration could also not be made. This changed with the publication of new speckle data of the wide pair, A-B, by Turner *et al.* (2008), who also fitted orbital elements to the astrometric positions with a period of 157 years.

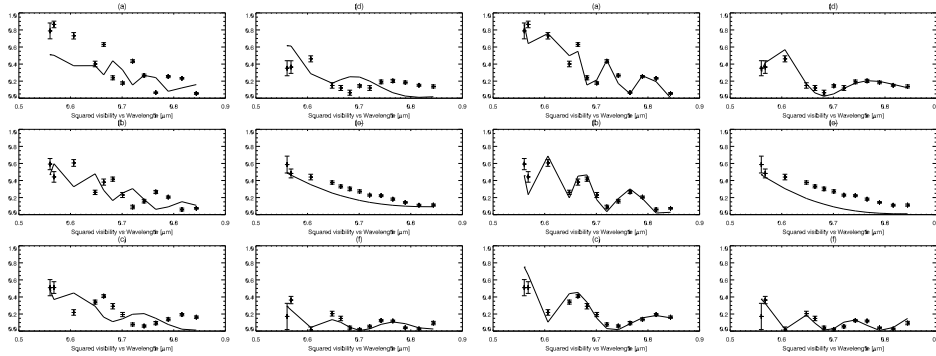


Figure 2: Visibility amplitudes of  $\sigma$  Ori, on the left with a model based on Turner's orbit, on the right with a modified orbit made to fit the tertiary position obtained from the NPOI data and a grid search procedure. Each panel shows the visibility amplitude on the N-W baseline as a function of wavelength for six different observations in the same night (March 25, 2012). One can see on the left, that Turner's orbit is a good fit for specific baseline orientations occurring later in the night, which are less sensitive to the offset of Turner's orbit.

Now, the Turner orbit could be used to predict the location of the tertiary component, and as it turned out, the not too different magnitudes of the three components conspired to produce rather complex variations of the visibility amplitude as a function of time, baseline, and wavelength. However, the accuracy of the Turner orbit was not sufficient to bring the predicted position of the B component within reach of a non-linear least-squares procedure to fit the exact location, as we show in Figure 2. Therefore, we used a grid search procedure to determine the global minimum of  $\chi^2$  in a small area centered on the prediction location, and then modified a Turner's orbit (semi-major axis and periastron angle only) to bring this

orbit into agreement with the NPOI results. The offset was about 5 mas.

Using the improved orbit for the wide pair, we modeled individual nights with enough data to constrain separation and position angle of the close pair. The eccentricity of the close pair was already known to be high, and this is confirmed by our preliminary NPOI results shown in Figure 3. The preliminary apparent visual magnitudes of the components were determined to be  $V_{Aa} = 4.4$ ,  $V_{Ab} = 4.9$ , and  $V_B = 6.0$ .

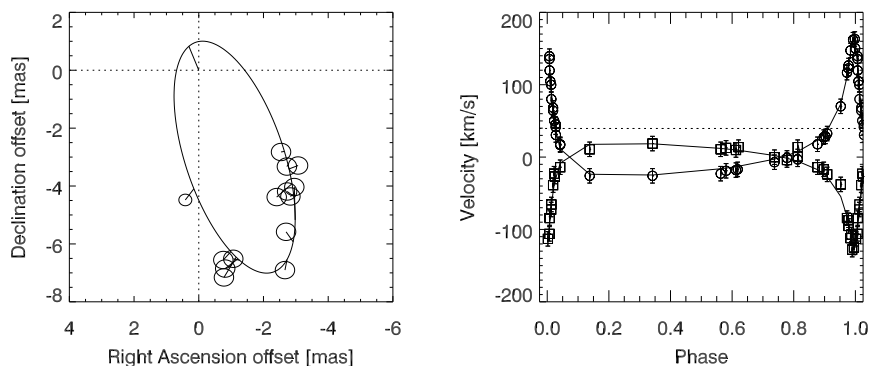


Figure 3: Orbits of  $\sigma$  Orionis A. Squares denote radial velocities of the primary, circles those of the secondary.

Using unpublished radial velocity data (F. Walter, priv. comm.) for both components, we can now fit the stellar masses, resulting in  $M_A = 16.7M_\odot$ , and  $M_B = 12.4M_\odot$ . The preliminary orbital parallax is 2.6 mas, while Hipparcos measured 3.0 mas (van Leeuwen, 2007).

### 3.3. $\xi$ TAURI

This quadruple system consists of a distant F-type star (component C) in a 51 year orbit (Rica Romero, 2010) around a hierarchical triple. The latter consists of a pair(components Aa and Ab) of A-type stars (Bolton and Grunhut, 2007) in orbit around a B-type star (component B). Component A ( $P = 7.15$  days) was not resolved by NPOI, but the pair A-B was, with a separation of up to 20 mas. A preliminary orbit is shown in Figure 4.

In these proceedings, J. Nemravová and collaborators report spectro-

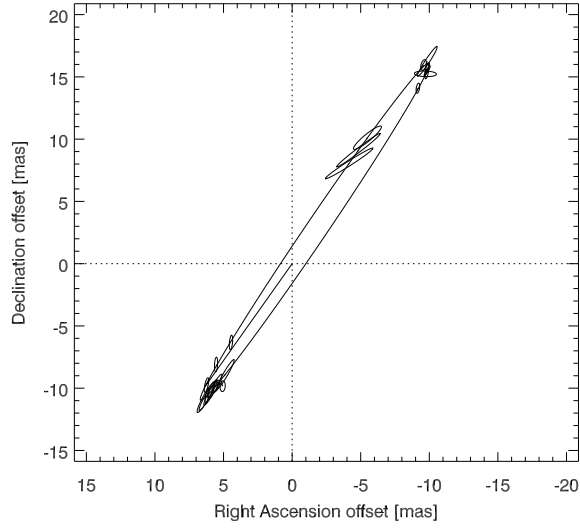


Figure 4: Orbit of  $\xi$  Tauri.

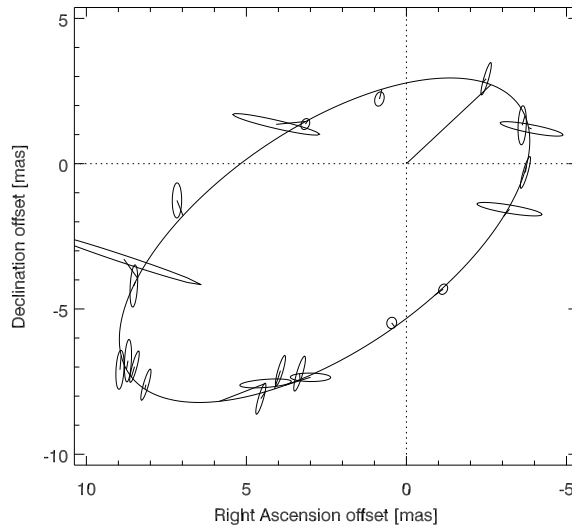


Figure 5: Astrometric orbit of HR 6493. Note that the error ellipse elongated in an East-West direction are associated with data from the (no longer in operation) Mark III Stellar Interferometer (Hummel, 1997).

scopic analysis of this multiple system, providing evidence for apsidal motion at a rate of 3.3 degrees per year. The NPOI observations span a period of 14 years, however, no significant apsidal motion appears to be present. More observations are planned to address this discrepancy.

### 3.4. HR 6493

As an example of an external collaboration, we present results of NPOI observations of the double star HR 6493, which has a primary of spectral type F3V. No tertiary component was found by Tokovinin *et al.* (2006).

### 3.5. B PERSEI

An ellipsoidal variable in a triple system, b Persei is also a radio star displaying non-thermal flares (Hjellming and Wade, 1973). The star is a single-lined spectroscopic binary with a period of 701 days and resembles Algol in spectral types and masses of the components, as well as in orbital parameters (Hill *et al.*, 1976; Zavala *et al.*, 2010). There is the possibility of eclipses of the close pair by the tertiary, as a minimum of light on JD 2450022.5 was reported by Hegedus *et al.* (1996), and also the NPOI measurements only show radial motion of the tertiary.

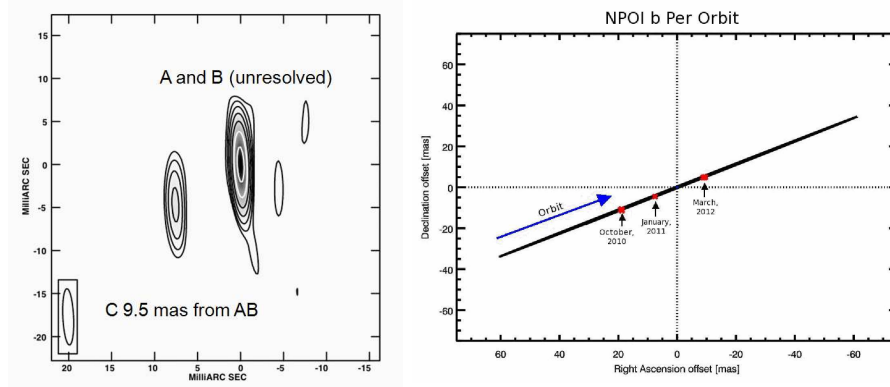


Figure 6: Map of the radio star b Persei, and preliminary orbit based on the existence of eclipses.

### Acknowledgements

The Navy Precision Optical Interferometer is a joint project of the Naval Research Laboratory and the US Naval Observatory, in cooperation with Lowell Observatory, and is funded by the Office of Naval Research and the Oceanographer of the Navy. The authors thank Jim Benson and the NPOI observational support staff whose efforts made this project possible. We thank Dr. F. Walter for allowing us the use of his unpublished radial velocities obtained with SMARTS at CTIO. The data used for the radial velocities of  $\zeta$  Orionis are due a collaboration with T. Rivinius, O. Stahl, and M.-F. Nieva, taken at the observatories of La Silla, Chile, Calar Alto (Spain), Cerro Armazones (Chile), and Haute Provence, France. We thank R. Chini for the BESO spectra taken at Cerro Armazones.

### References

- Armstrong, J. T., Mozurkewich, D., Rickard, L. J., Hutter, D. J., Benson, J. A., Bowers, P. F., Elias, II, N. M., Hummel, C. A., Johnston, K. J., Buscher, D. F., Clark, III, J. H., Ha, L., Ling, L., White, N. M., and Simon, R. S.: 1998, *Astrophys. J.* **496**, 550.
- Benson, J. A., Hutter, D. J., Elias, II, N. M., Bowers, P. F., Johnston, K. J., Hajian, A. R., Armstrong, J. T., Mozurkewich, D., Pauls, T. A., Rickard, L. J., Hummel, C. A., White, N. M., Black, D., and Denison, C. S.: 1997, *Astron. J.* **114**, 1221.
- Bolton, C. T.: 1974, *Astrophys. J., Lett.* **192**, L7.
- Bolton, C. T. and Grunhut, J. H.: 2007, in W. I. Hartkopf, E. F. Guinan, and P. Harmanec (eds.), *IAU Symposium*, Vol. 240, p. 66.
- Hegedus, T., Biro, I. B., Borkovits, T., and Paragi, Z.: 1996, *Information Bulletin on Variable Stars* **4340**, 1.
- Hill, G., Aikman, G. C. L., Cowley, A. P., Bolton, C. T., and Thomas, J. C.: 1976, *Astrophys. J.* **208**, 152.
- Hjellming, R. M. and Wade, C. M.: 1973, *Nature* **242**, 250.
- Hummel, C. A.: 1997, in K.-C. Leung (ed.), *The Third Pacific Rim Conference on Recent Development on Binary Star Research*, *ASP Conf. Ser.* **130**, p. 19.
- Hummel, C. A.: 2010, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 7734, p. 77.
- Hummel, C. A., Benson, J. A., Hutter, D. J., Johnston, K. J., Mozurkewich, D., Armstrong, J. T., Hindsley, R. B., Gilbreath, G. C., Rickard, L. J., and White, N. M.: 2003, *Astron. J.* **125**, 2630.

- Hummel, C. A., White, N. M., Elias, II, N. M., Hajian, A. R., and Nordgren, T. E.: 2000, *Astrophys. J., Lett.* **540**, L91.
- Rica Romero, F. M.: 2010, *Rev. Mex. Astron. Astrofis.* **46**, 263.
- Rivinius, T., Hummel, C. A., and Stahl, O.: 2011, in C. Neiner, G. Wade, G. Meynet, and G. Peters (eds.), *IAU Symposium*, Vol. 272, p. 539.
- Simón-Díaz, S., Caballero, J. A., and Lorenzo, J.: 2011, *Astrophys. J.* **742**, 55.
- Tokovinin, A., Thomas, S., Sterzik, M., and Udry, S.: 2006, *Astron. Astrophys.* **450**, 681.
- Turner, N. H., ten Brummelaar, T. A., Roberts, L. C., Mason, B. D., Hartkopf, W. I., and Gies, D. R.: 2008, *Astron. J.* **136**, 554.
- van Leeuwen, F.: 2007, *Astron. Astrophys.* **474**, 653.
- Zavala, R. T., Hummel, C. A., Boboltz, D. A., Ojha, R., Shaffer, D. B., Tycner, C., Richards, M. T., and Hutter, D. J.: 2010, *Astrophys. J., Lett.* **715**, L44.